

Dimensional Metrology

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Program Funding:	\$4 M
FTEs	19

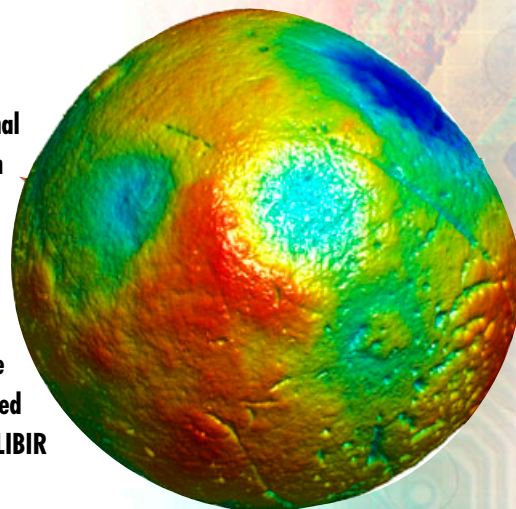
Program Goal

Develop and deliver timely dimensional measurements and standards to address critical U.S. industry needs for traceable dimensional metrology, particularly for the support of trade and innovation, process control, and quality in manufacturing from the micro- to the macro-scale.

Problem

Dimensional metrology spans a vast array of products and industries, from large scale manufacturing of ships and aircraft, to miniaturized mechanical components, to precision optics. The globalization of manufacturing has resulted in complex products with components produced all over the world that must assemble and function seamlessly. Accurate dimensional metrology is essential to meeting this goal. New manufacturing technology is entering industry continuously and often has little or no supporting metrology. NIST, positioned at the top of the traceability pyramid, is challenged to support this broad network of industrial and laboratory dimensional measurements.

Three dimensional representation of the form error of a 100 mm diameter silicon sphere measured by XCALIBIR



Approach

The dimensional metrology program seeks to realize and disseminate the SI (Système International d'unités) unit of length across a wide range of calibration services and artifacts, and to support industrial dimensional metrology through national and international measurement standards. The program funds calibration services and standard reference materials, along with their associated quality assurance programs. The program also identifies and supports research and development (R&D) for new and emerging measurement needs including: (1) precision optics with emphasis on aspheric and free form optics; (2) 3D coordinate measurement of miniaturized features; and, (3) complex 3D surfaces including large scale optical metrology, scanning probe evaluations, and data fitting.

Typical Customers and Collaborators

Department of Defense (DOD), Department of Energy, aerospace industry, automotive industry, heavy equipment and machinery industry, state weights and measures labs, and metrology instrumentation manufacturers.

dimensional metrology

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19

Annual Program Funds:
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Customer Need & Intended Impact

Dimensional metrology spans a vast array of products and industries, from large scale manufacturing of ships and aircraft to miniaturized mechanical components to precision optics. The Dimensional Metrology Program, as part of a national measurement institute, plays a crucial role in providing metrology infrastructure and calibrates approximately 5,000 master gauges, instruments, and artifacts per year. Although the calibrations performed by the program represent a minuscule fraction of the total number of dimensional measurements performed in the U.S. annually, they typically represent the highest level of measurement accuracy and provide a cost effective way to achieve traceability to the SI (International System of units) units.

Under cost cutting pressures, U.S. industry is frequently unable to maintain in-house metrology expertise and increasingly relies on documentary standards to select and maintain metrology equipment. Accordingly, the program actively participates in the development of national standards and represents the U.S. in the development of international standards. At the national standards level, these documents provide tutorial information and enable cost savings for both suppliers and customers of metrology equipment by providing standardized practices and specifications. At the international standards level, the program supplies a high level of metrological expertise, providing a strong voice to address specific U.S. metrology needs in the ISO standardization process, and ensures that non-tariff trade barriers are not erected.

Industrial manufacturing is continually evolving and creating new measurement challenges for NIST. The Dimensional Metrology Program identifies and supports research and development (R&D) to meet these new measurement needs. Competitive pressures on U.S. manufacturing arising from globalization guide this selection process. As developing economies enter a product field they

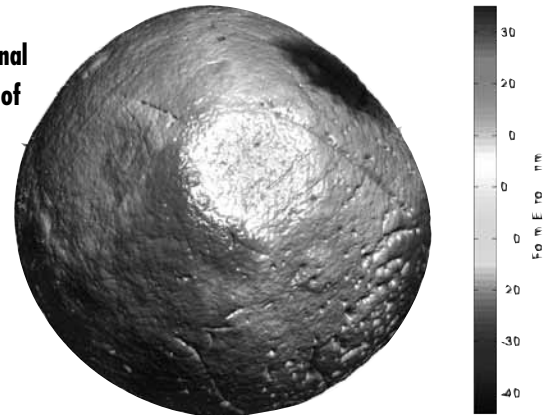
typically displace domestic suppliers. Domestic manufacturing must continually move up the manufacturing food chain out of reach of commodity-based products. Such an effort requires more sophisticated product designs that frequently involve components that have complex geometries or are miniaturized, or both. In optics, this means aspheric and free form surfaces. In discrete parts, this involves complex surface shape. In these cases conventional measurement methods are either not possible or poorly suited for the task.

Precision Metrology for Complex Optics

Precise optical figure metrology is a leading edge technology, enabling multiple industries. The drive for ever-finer integrated circuit (IC) features demands diffraction-limited imaging; leading-edge steppers seek a wavefront better than 2 nm root mean square (RMS) for adequate imaging. This net wavefront error must be shared between the surface errors of as many as 20 lenses, including aspheric lenses. Wafers on the chuck of the stepper or other tool also need ever-improved flatness to address the depth of field issue. No U.S. SI-traceable metrology system is in place for measuring optical figure, wavefront distortions, or wafer flatness; few industry standards exist, and those that do are often outdated.

Complex surfaces in optics are exploding in their applications. Consumer products such as digital cameras and DVDs are driving the optics industry to use small, fast aspheric optics. Several attendees at the American Society for Precision Engineering (ASPE) meeting on Precision Interferometry in May 2000 identified traceable measurement of aspheric optics as a key need. Traceability involves valid

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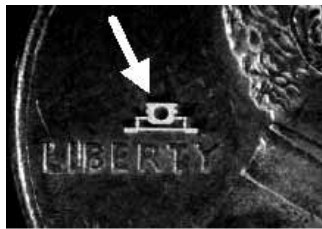
uncertainty statements that are rare in the U.S. optics industry. Only a small number of very specialized optical companies practice the metrology of aspheric and free form optics. The barrier to entry to this field is high in both capital equipment and expertise. The Dimensional Metrology Program seeks to lower this barrier by making this form of optical metrology available to a wide array of smaller manufacturers. The program also seeks to establish a traceability path for optical metrology.

Micro-features

Metrology for micro-features is one of the most active areas in dimensional metrology. The National Measurement Institutes (NMIs) of NPL (UK) and PTB (Germany) are both building custom coordinate measuring machines (CMMs) designed solely for very small parts. Machined micro-features represent a rapidly expanding array of products produced by such techniques as micro-machines and LIGA (a German acronym for Lithography, Electroplating, and Molding). Small features in optical lenses, optical fibers and their connectors, DNA processing chips, drug delivery systems, and a myriad of other applications are increasingly common.

These components are too delicate to inspect with conventional contact probing techniques, including the program's Moore M48 CMM.

New probe technology for microfeatures will provide the measurement infrastructure needed to characterize micro-scale devices entering the marketplace. For example, fuel injectors with holes as small as 60 μm in diameter would benefit from precision measurement so as to standardize dimensions, thus increasing fuel economy and reducing pollution; even a 0.4% increase in fuel efficiency would represent \$1 B annual savings to the U.S. As another example, the \$3 B telecommunication



Metallic LIGA component from Axsun Technologies

connector market would benefit from the ability to measure the geometry of fiber ferrules or similar fiber alignment devices used in optical switches. Sub-micron alignment

is needed to minimize connection losses, and consequently very small measurement uncertainties are desirable. Previously MEL supplied a Standard Reference Material (SRM) for the external diameter of an optical fiber and the program now seeks to provide an SRM for the internal diameter of an optical ferrule. More generally, whereas the \$1 B American micro electro-mechanical systems (MEMS) industry relies on image-based measurements at modest accuracy, we can expect that a maturing MEMS industry will face the same needs for progressive precision as seen in manufactured products on a larger scale; NIST should be in a position to meet this emerging need.

Complex Surface Metrology

Complex surfaces are increasingly employed in manufacturing, especially for large components. Not surprisingly a boom in instruments and methodologies to measure these structures is underway. A wide range of technologies such as multilateration, photogrammetry, LADAR (Laser Detection & Ranging), and structured light are rapidly advancing due to the availability of high-speed electronics and inexpensive computer power. The U.S. is a major supplier of frameless metrology systems used in scanning large structures, however, demonstrating their metrological capability is problematic. In a 2003 workshop chaired by NPL, PTB, and NIST on large-scale measurement systems, one of the summary findings stated "So far, no common procedures for the evaluation of measurement uncertainty or for performing an interim check are in existence for large-scale measurement systems. In the near future, the rigorous implementation of quality systems, not just in the aircraft and automotive industries, but in a wide context will generate a huge need for action in this area."

The problem is typified by NIST's Building and Construction Research Division (BCRD) that plans to use a three-dimensional (3D) LADAR measurement system to establish the "true value" of a construction measurement test course against which other measurement systems are evaluated. Unfortunately, they have no means to evaluate the accuracy of the LADAR system and, hence, its contribution to calibration errors in the test course. BCRD is very interested in having the LADAR system evaluated in a metrologically rigorous manner.

Complex mechanical surfaces often act as the interface with their environments in dynamic structures such as airframes, turbine blades, and ship hulls. Small deviations in manufacturing or assembly prevent optimal function and cause inefficiencies that can consume large quantities of energy. It is often said that aircraft are actually “powered corkscrews” indicating that small deviations from the designed form create drag that degrades performance. Accurate metrology can minimize these effects. Major manufacturers such as Boeing, Caterpillar, and Pratt & Whitney increasingly rely on measurements of complex surfaces by frameless measurement systems. Traditional methods such as large fixed CMMs represent large fixed capital investments and are not reconfigurable as required in a flexible manufacturing environment.

The program seeks to focus on metrology instruments that are used in advanced manufacturing of complex surfaces. We anticipate providing rigorous calibrations of a wide class of instruments that will facilitate better instrument selection by metrology practitioners, improved designs by instrument manufacturers, and traceability of these measurement systems. The program is also researching conventional CMM probing systems and associated data fitting for complex surfaces.

Technical Approach & Program Objectives

Objective #1: NMI Services

Provide practical access to the SI unit of length and angle through calibrations and standard reference materials, and to support industrial metrology through national and international standards.

The program takes a broad approach to improving all aspects of measurement services and standardization. High quality measurement services are ensured by a program wide quality assurance plan and audits based on ISO 17025. Measurement services include active participation in the BIPM (International Bureau of Weights and Measures, France) sponsored Working Group (WG) for Dimensional Metrology and the international measurement intercomparisons required by the NIST participation in the CIPM (International Committee for Weights and Measures) Mutual Recognition Arrangement. Funding is focused on calibrations with a wide customer base, and less important measurement services are terminated. Program goals include lowering measurement uncertainty, expanding measurement range, and improving on-time delivery. Program staff with specific metrology expertise are involved in both national (ASME - American Society of Mechanical Engineers) and international (ISO TC213 – Technical Committee on Dimensional and geometrical product specifications and verification) metrology standards development. Participation also includes the Joint Committee for Guides to Metrology (JCGM WG1), an international effort that produced the ISO Guide to the Expression of Uncertainty in Measurement. Program staff also provide metrology tutorials to industrial audiences.

Objective #2: Optical Metrology for Complex Surfaces

Develop the instrumentation, methodologies, and expertise to calibrate complex geometry optics - aspherics and free-forms - with sub-nanometer figure uncertainty, for size capacities up to 300 mm diameter for XCALIBIR and 100 mm for GEMM.

Optics is a pervasive enabling technology, and is critical to microelectronics fabrication, consumer electro-optics, remote sensing, defense, medical imaging, and other areas. Worldwide interest in applying aspheric and free form optics is strong, and the need for better metrology in these areas is critical. A key challenge for the measurement of aspheres and free form optics is the necessity to generate a reference wavefront that matches the optical surface under test. The optics used to generate reference wavefronts are called “null lenses.” They are costly to make and use, are not reconfigurable, and increase the measurement uncertainty. This objective researches alternative approaches that do not require null lenses: subaperture stitching using both the phase measuring and displacement measuring interferometers of X-Ray Calibration Interferometer (XCALIBIR), the Geometry Measuring Machine (GEMM), and computer generated holograms (CGH). The combination of the three approaches will yield a unique facility for aspheric measurements and provide a means for detecting unknown systematic errors within each method. Additionally, reversal methods that are used to determine the wavefront errors in the interferometer as well as the test optic (and hence are also important to aspheric measurements) are known to have discrepancies between different techniques. XCALIBIR will examine self-calibrating methods and determine their relative uncertainties resulting in improved optical figure accuracy.

Objective #3: Micro-feature Dimensional Metrology

Develop and characterize advanced CMM probing technologies to bring micro-feature (size range: 100 μm – 500 μm) measurement capacity to a level suitable for NIST SP-250 (a publication that lists calibration services) calibrations.

New fabrication technologies are rapidly expanding the array of products with microfeatures. This objective seeks to develop the capability to extend 3D coordinate metrology to the 100 μm feature size, with the added complication of feature aspect ratios of over 50:1. First, several new probe technologies that may be suitable for micro-feature use on the Moore M48 CMM will be investigated. Current work based on a PTB design of a fiber optic probe, in a very rudimentary prototype constructed at NIST, has shown promising results. Alternatively, a MEMS-based probe design (also under development by PTB) will be investigated as a longer-term solution. Different sensor-based technologies will be examined, in particular, for the ability to measure deep holes having aspect ratios approaching 100:1. Secondly, commercial instruments that are pushing this feature size domain, such as Mitutoyo’s Ultra UMAP CMM will be investigated under a Cooperative Research And Development Agreement (CRADA) agreement. Thirdly, the program anticipates a CRADA with United Technologies Pratt & Whitney and Oak Ridge Y-12 for the development of measurement methods, reference artifacts, and uncertainty budgets for inspection of small (250 μm to 500 μm) holes in turbine blades. Finally, 2D surface topography will be investigated by both white light interferometry and by phase shifting interferometry microscopy. Some algorithms for stitching interferograms developed under Objective #2 may be used in this effort.

Objective #4: Complex Geometry Dimensional Metrology

Develop metrological capabilities and facilities to calibrate instruments and probing technology capable of collecting large data sets on complex geometry surfaces.

Complex geometry surfaces are among the most challenging areas of dimensional metrology. Some of the difficulties include the complexity of scanning probes, the optical and mechanical metrology in the measuring instruments, huge data files, and fitting algorithms for these surfaces. Most of these instruments are sufficiently transportable (unlike conventional CMMs) that testing at NIST is a reasonable procedure. The program seeks to develop a calibrated test range traceable to the SI unit of length for frameless coordinate measurement systems. Use of the test range by instrument manufacturers may lead to improved accuracy through the discovery of unknown systematic errors.

Scanning probes for conventional CMMs are gaining widespread use for inspecting complex workpieces. These probes are, in effect, miniature three axis CMMs with a very short thermal time constant. All of the thermally induced errors normally associated with CMM structures can also appear in the probe and are accentuated due to the short time constraint. The program will test CMM scanning probes in the NIST Advanced Measurement Laboratory's (AML) thermally controllable lab to simulate conditions on the shop floor.

Finally, the program seeks to develop an E-metrology effort where coordinate metrology information, and in particular, data sets and their associated algorithm fits can be readily accessed by industry. This is an expansion of the current Algorithm Testing System (ATS) into the domain of complex surfaces and large data sets.

Major Accomplishments

Objective 1: NMI Services

- Completed final draft of ASME 89.7.4 “Measurement Uncertainty and Risk Analysis”; this provides the link between measurement uncertainty and the consequences of workpiece acceptance or rejection (FY2004)
- Improved measurement services for ball diameter and roundness, 10% reduction in uncertainty with no increase in calibration prices (FY2004)
- Publication of ASME B89.7.3.3 “Guidelines for Assessing the Reliability of Dimensional Measurement Uncertainty Statements”; resolves conflicts between supplier and customer concerning the evaluation of measurement uncertainty (FY2003)

Objective 2: Optical Metrology for Complex Surfaces

- Produced and published “Measuring Form and Radius of Spheres with Interferometry” in International Institution for Production Engineering Research (CIRP); one of the first reconciliations of figure measurements with displacement of radius measurements
- Completed design of the Geometrical Measuring Machine (GEMM) world’s first 2D interferometer with null free optic for free from optics (FY2004)
- Completed 300 mm diameter 3-flat tests with 0.5 nm repeatability using XCALIBIR, establishing it as an NMI class instrument (FY2003)

Objective 3: Micro-features metrology

- Constructed and tested a 2D optical fiber probe with 15 nm one sigma repeatability; establishes that a 2D probe with $U(k=2) < 0.1 \mu\text{m}$ is feasible (FY2004)
- Obtained Mitutoyo Ultra UMAP CMM with micro probe on a CRADA (FY2004)

Objective 4: Complex Geometry Dimensional Metrology

- Completed final draft of ASME 89.4.19 “Laser Tracker Performance Evaluation”; world’s first metrology standard for spherically based coordinate measurement systems (FY2004)
- Organized Coordinate Measurement Systems Committee (CMSC) session on Large Scale Metrology Systems; including PTB and NPL coordinating international activities (FY2004)
- Keynote address and paper on large scale metrology to CIRP establishing NIST as a significant contributor to this field (FY2003)

FY2005 Projects

Calibration Services, SRMs, and Intercomparisons (Objective #1)

The Dimensional Metrology Program produces a large number of calibrations and Standard Reference Materials in support of industrial measurement needs. These services are supplied under ISO 17025-based Quality System.

Deliverables for FY2005:

1. A 10% increase in the percentage of on-time delivery of calibration services.
2. The performance of the Moore M48 CMM for one, two and three dimensional measurements remapped and verified.
3. Calibration service for coefficient of thermal expansion calibration submitted to Measurement Services Advisory Group (MSAG) for approval.
4. Working Group for Dimensional Metrology (WGDM) Drafts for Key Comparison K-6, Diameter.
5. Report of internal audit on MEL's Precision Engineering Division (PED) Quality System. PED Quality System modified to bring SRM development into conformance with the NIST Quality Manual.

National and International Standards (Objective #1)

This project is directed to the development of national and international standards. The list of standards in the section below are standards that program staff either chair or are the primary authors.

Deliverables for FY2005:

1. Publication of ASME B89.7.4 on uncertainty and risk analysis.
2. Final Draft of ASME B89.4.19 for laser trackers
3. Final Draft of ASME B89.7.3.2 regarding measurement uncertainty.
4. Draft International Standard status - ISO 10360-2 on CMMs for measuring linear dimensions.
5. Draft International Standard status - ISO 10360-5 on CMM Probing Systems.
6. Corrigendum to TC 213 regarding U.S. concerns on ISO 14253-1 Decision Rules submitted.
7. Working Draft for ASME B89.4.1 CMM Performance Evaluation compatible with ISO 10360 series.

Optical Metrology of Spheres, Flats, Mild Aspheres (Objective #2)

This project focuses on the characterization of measurement methods and absolute error separation techniques to determine and reduce the uncertainties of measurements made with commercially available Phase Measurement Interferometers.

Deliverables for FY2005:

1. Archival publication demonstrating the capability of XCALIBIR to measure flats and spherical optics with standard uncertainties of 0.2 nm for figure and 20 nm for radius of curvature.
2. Ray-trace model of XCALIBIR to quantify retrace errors that occur during the measurement of aspheres.
3. Figure measurement of near-cylindrical aspheric mirror mandrels for the NASA Constellation-X project.
4. Prepare for move of XCALIBIR to the AML.

Project: Optical Metrology of Aspheres (Objective #2)

This project develops a complementary set of techniques: interferogram stitching, GEMM, and CGH, for the absolute measurement of aspheric optics with uncertainties at the nanometer level.

Deliverables for FY2005:

1. A prototype GEMM instrument useful for 1-D profiling of free form optics.
2. Demonstration of asphere measurement with XCALIBIR stitching algorithms.
3. A set of test aspheres.

Wafer Metrology (Objective #2)

This project will develop an inferred interferometer (IR^2) measuring thickness variation in silicon wafers.

Deliverables for FY2005:

1. IR^2 instrument operational.
2. Demonstration of IR^2 measurement of thickness of 300 mm wafers to less than 5 nm uncertainty. The sample population will include certified 300 mm wafers from several suppliers and single side polished wafers provided by WaveFront Sciences Inc.

Micro-Feature Probe R&D (Objective #3)

The focus of this project is to develop new probe technology for the Moore M48 that can measure feature sizes of 100 μm . The probe requires an uncertainty of $U_{k=2} \leq 100$ nm and a probing force ≤ 20 mN.

Deliverables for FY2005:

1. Paper on 2D fiber optic probe performance published at American Society for Precision Engineering (ASPE).
2. Paper published at National Conference of Standards Laboratories (NCSL) on small hole metrology.

UMAP CMM and Surface Interferometry (Objective #3)

This project focuses on the Mitutoyo UMAP CMM, a state of the art commercial instrument to measure micro-features. This instrument immediately gives the program the ability to measure features as small as 100 μm with $U_{k=2} = 300 \text{ nm}$. The instrument will be characterized and serve as a cross reference for ongoing probe development work. Surface interferograms using white light and phase shifting interferometry will also be characterized for surface reconstruction.

Deliverables for FY2005:

1. A paper on the observations and analysis of methods divergence between white light and phase shifting interferometry for surface roughness measurements.
2. A report on the intercomparison of 0.5 mm diameter holes measurements with Moore M48 CMM.
3. Error map and detailed uncertainty budget for micro-feature measurements on the UMAP.

Complex Geometry Metrology Test Range (Objective #4)

This project seeks to develop a calibration test range applicable to a wide range of different measurement technologies including systems that require either optically cooperative or uncooperative targets.

Deliverables for FY2005:

1. Report from a NIST-lead workshop at the CMSC on the calibration needs of large-scale coordinate metrology community.
2. Large Scale Lab refurbished for floor and ceiling work.
3. Report on targets and target mounting.
4. Report on calibration strategies for test range.

High Data Density Probe Performance (Objective #4)

This project seeks to test scanning probes in a simulated industrial thermal environment.

Deliverables for FY05:

1. Integration of UCC1 controller into the REI CMM.
2. Report on performance of integrated probing system when tested with the entire ISO suite of probe performance tests.

E-Metrology of Complex Surfaces (Objective #4)

This project involves construction of the program website, posting as much MEL dimensional metrology information as possible, and the development of downloadable data sets to test metrology software. Data sets will include Algorithm Testing Service (ATS) data, surface metrology data, complex surface data, and Geometric Dimensioning and Tolerancing (GD&T) features with respect to datum reference frames.

Deliverables for FY2005:

1. Surface roughness algorithm database and analysis available on website.
2. Dimensional Metrology Program available for Internal NIST website.

Typical Customers and Collaborators

Customers:

Department of Defense, Department of Energy, aerospace industry, automotive industry, heavy equipment and machinery industry, state weights and measures labs, and metrology instrumentation manufacturers.

Collaborators:

Argonne National Laboratory's Advanced Photon Source; WaveFront Sciences Inc.; Mitutoyo of America; United Technologies Pratt & Whitney; Oak Ridge Y-12; The Boeing Company; Automated Precision Inc.; Renishaw Inc. , and NIST Building Construction and Research Division.

FY2005 Standards Participation

- ASME B89.1.8 Laser Interferometers
- ASME B89.1.9 Gage Blocks
- ASME B89.4.1 U.S. CMM standard including scanning probe technology
- ASME B89.4.19 Optical CMMs including laser trackers
- ASME B89.4.20 Traceability of CMM calibrations
- ASME B89.4.22 Articulating Arm CMMs
- ASME B89.7.3 Measurement Uncertainty: Decision Rules
- ASME B89.7.4 Measurement Uncertainty: Risk Analysis
- ASME B89.7.8 Traceability of Dimensional Measurements
- ASME B46 Surface Texture
- ISO TC213 WG4 International standards on measurement uncertainty
- ISO TC213 WG10 International standard on Coordinate Metrology
- ISO TC213 planetary Dimensional and Geometrical Product Specifications and Verification
- OSA Optical Society of America, "Optical Design and Instrumentation Group"

FY2005 Measurement Services

The Dimensional Metrology Program offers calibration services, including: gauge blocks, tapes and scales, length standards, sieves, algorithm testing, diameter measurements, American Petroleum Institute (API) gauges, optical reference planes, roundness standards, angular measurements, laser measurements, and surface texture.

Dimensional Metrology

